A STUDY OF INTERNAL COMBUSTION ENGINE PERFORMANCE AS AFFECTED BY THE EVAPORATION OF WATER INTO THE ENTERING FUEL AND AIR MIXTURE.

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by

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Approved:

Date Approved by Chairman May 17, 1957

ACKNOWLEDGEMENTS

I wish to express my appreciation to Professor R. L. Allen for suggesting this problem and also for his aid in the pursuance of the work. I would also like to thank Professor W. A. Hinton for his many suggestions and Mr. T. D. Sangster and Mr. J. W. Davis for their aid in the construction of the test engine. Lastly I thank Martha MacCullen, my wife, who aided me greatly in this work.

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LIST OF ABBREVATIONS

a	discharge coefficient
a_2	area of the air orifice, $feet^2$
B. H. P.	brake horsepower
B. S. F. C.	brake specific fuel consumption
CCl_4	carbon tetrachloride
$^{\circ}$	degrees
$^{\circ}F$	degrees farenheit
G	rate of air flow, pounds / second
G^1	rate of air flow, pounds / minute
g	acceleration of gravity, feet / $second^2$
$h_1 - h_2$	pressure drop across air orifice, inches of water
hg	mercury
H. P.	horsepower
in.	inches
lb(s)	pound(s)
m	ratio of area of air orifice to area of air pipe
min.	minute
p_1'	pressure above the air orifice, pounds / $foot^2$
p_2'	pressure below the air orifice, pounds / $foot^2$
R. P. M.	revolutions per minute
v_1	specific volume of air above air orifice, $feet^3$/ pound
ρ_1	density of air above air orifice, slugs / $foot^3$

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INTRODUCTION

Purpose

Much study has been devoted to the problem of knocking in the Otto cycle engine. The suppression of knocking by the addition to the fuel of various compounds such as tetraethyl lead, has been shown to be feasible. Also it has been shown that the addition of water and water-alcohol mixtures to the fuel-air mixture entering the engine has a decided effect in reducing the tendency of the engine to knock. In making a study of the benefits of the addition of water, the question arises as to the relative benefit of the cooling effect produced by the evaporation of the water and the benefit produced by the H_2O molecule being present during the combustion process.

Objective

It is the objective of this investigation to obtain data from the operation of an Otto cycle engine to show the relative merits of the addition of H_2O as a liquid to the entering fuel-air mixture and of the addition of H_2O as a vapor to the entering fuel-air mixture.

EQUIPMENT

Engine:

The engine used for this thesis was a four cylinder Continental Red Seal Engine, whose bore was 2 1/2 inches and whose stroke was 3 1/2 inches giving a displacement of 68.7 cubic inches. A special head was used to give a compression ratio of 7.2 to 1. (See Figure 5, Page 23).

Engine Cooling System:

The jacket cooling water was supplied from the city water line through a valve and calibrated orifice and discharged into the laboratory sewer. This system allowed the average jacket water temperature to be maintained constant during the test runs and also allowed the rate of flow to be measured. (See Figure 1, Page 19).

Dynamometer:

The power output of the engine was absorbed by a Taylor hydraulic dynamometer which was connected to the engine with an automotive type universal joint. The dynamometer was connected to a Fairbanks scale so the load applied to the dynamometer could be measured. (See Figure 1, Page 19).

Ignition System:

The distributor which came installed on the engine was taken apart and the flyweights were locked in the closed position. A plate marked in degrees was then installed and a pointer indicator attached to the distributor housing indicating the advance or retard of the spark, in degrees, relative to the top center position of the piston. (See Figure 5, Page 23).

Water Injection System:

The water injection system consisted of an "Octa-gane '50' Injector" with a special injection flange mounted between the carburetor and the intake manifold. The "Octa-gane '50' Injector", a commercial water injector, makes use of the pressure differential between the exhaust and intake manifolds to inject water into the intake manifold. The rate of injection was controlled by means of a needle valve. The injection water tank was mounted on a Toledo scale to permit weighing of the water used. The special injection flange consisted of a steel flange matching the mounting flange of the carburetor with a 1/8 inch diameter copper tube, cut diagonal at the end, extending to the center of the opening. (See Figure 2, Page 20).

Steam Injection System:

The steam injection system consisted of a line from the laboratory main passing through a throttling valve and a 1/8 inch diameter orifice and entering the engine by means of the same injection flange as used for the water injection. Petcocks were installed on both the water and steam lines to permit the use of the same injection flange. Since the steam was slightly superheated on entering the engine, Its temperature and pressure were measured as indicated in the paragraph on miscellaneous instruments. The orifice was calibrated prior to the actual engine tests so that the rate of steam injection could be accurately determined. (See Figure 3, Page 21).

Fuel System:

The fuel system of the engine consisted of a two gallon fuel can resting on a pair of Toledo scales, a fuel pump, and an up-draft carburetor. The fuel fed by gravity from the weighing can to the fuel pump. The carburetor had a variable main jet which allowed the carburetor to be adjusted to a best performance setting for making the test runs. (See Figure 5, Page 23).

Air Metering System:

The system for measuring the air flow to the engine consisted of a 0.850 inch diameter orifice installed between flanges on a 1 1/2 inch diameter pipe, with a manometer connected so as to indicate the pressure drop across the orifice, A 50 gallon surge tank was installed between the orifice and carburetor intake to damp out the pulsations in the intake air. (See Figure 4, Page 22).

Engine Instruments:

Instruments were mounted on the control panel to register engine speed, manifold pressure, oil pressure, exhaust pressure, and manifold vacuum. (See Figure 6, Page 24).

Miscellaneous Instruments:

The room wet and dry bulb temperatures were obtained with a sling psychrometer. The intake manifold temperature, the exhaust temperature, the temperature of the air entering the carburetor, the temperature of the cooling water entering and leaving the engine, and the temperature of the steam upstream and downstream from the orifice were all measured by means of iron-constantan thermocouples which were connected by a selector switch to a Leeds and Northrup direct reading type potentiometer. The potentiometer was calibrated by comparison with a standard mercury filled bulb thermometer. (See Figure 5, Page 23). The pressure drop across the cooling water orifice was measured by means of a manometer using carbon tetrachloride dyed with iodine as the fluid. (See Figure 6, Page 24). The pressure drop across the air orifice was measured by means of a manometer using oil with a specific gravity of 38 degrees Baume as the fluid. (See Figure 6, Page 24). The pressure drop across the steam orifice was measured by means of a manometer using mercury as the fluid. The static pressure above the orifice was measured by means of a bourdon tube gage. (See Figure 5, Page 23).

PROCEDURE

The operating procedure for gathering the data necessary for determining engine performance under normal conditions and then with liquid water injection and finally with steam injection was as follows:

In preparation for making the test runs the main jet of the carburetor was adjusted to slightly on the lean side of the best performance setting. The engine was then allowed to run under light load for a period of time sufficient for it to reach its normal operating temperature.

The first test was made with no water or steam injections to determine the basic performance of the engine for comparison with its performance with liquid water injection or steam injection. For this test the warmed-up engine was gradually brought up to the desired speed and then sufficient load was applied with the dynamometer to hold the speed constant while the throttle was opened to the maximum postion. Next the spark was advanced slowly until the first audible detonation was heard, then the distributor was locked in this position. The engine speed was checked and readjusted with the dynamometer if necessary. The engine was allowed to operate at these conditions for a period of time sufficient to allow equilibrium to obtain. Following this the test run was made and the following data were observed every five minutes during the test:

1. Weight fuel
2. Dynamometer load
3. Manifold pressure
4. Engine speed
5. Exhaust pressure
6. Pressure drop across cooling water orifice
7. Pressure drop across air orifice
8. Room wet bulb temperature
9. Room dry bulb temperature
10. Manifold temperature
11. Exhaust temperature
12. Air temperature before carburetor
13. Cooling water temperature increase
14. Spark advance.

The next four tests were made using liquid water injection. The same warm-up procedure was followed as for the first test with no injection. Then for the first water injection test the spark was advanced five degrees beyond the position of first audible knock as found in the original test. The next step was to bring the engine up to speed and then hold the speed constant with the dynamometer while the throttle was opened to the maximum postion. After this the needle valve on the "Octa-gane '50' Injector" was opened to allow a sufficient quantity of water to be injected to reduce the knock to the same intensity as in the original test. The engine speed was checked and readjusted with the dynamometer if necessary. The engine was allowed to operate at these conditions for a period of time sufficient to allow equilibrium to obtain. Following this the test run was made, and the same data were recorded each five minutes as for the original test with no injection, also the weight of water injected was observed and recorded. The above procedure was repeated for each water injection test with the exception that the spark was advanced an additional five degrees for each test.

The last four tests were made using steam injection. The same engine warm-up procedure was followed as previously described for the no-injection test. However in addition the inlet valve to the steam injection unit was opened slightly to allow this unit to come up to operating temperature to prevent condensation during the test runs. The procedure followed for bringing the engine up to conditions desired for testing and the actual test procedure were identical to those followed for the water injection tests with the exception that steam was injected instead of water.

RESULTS

The principle results which were obtained from this test can be enumerated as follows:

1. The further the spark was advanced the greater the quantity of water required to suppress the detonation;[1]

2. The further the spark was advanced the greater the quantity of steam required to suppress the detonation;[1] Also the steam required was greater than the water required to give the same suppression;

3. As the spark was advanced the brake horsepower decreased, decreasing more with steam injection than with water injection;[2]

4. As the spark was advanced the brake specific fuel consumption increased, increasing more with steam injection than with water injection;[3]

5. As the spark was advanced the volumetric efficiency increased slightly with water injection and decreased with steam injection;[4]

6. The manifold temperature decreased with increased water injection and increased with increased steam injection;[4]

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[1]See Figure 7, Page 28

[2]See Figure 8, Page 29

[3]See Figure 9, Page 30

[4]See Figure 11, Page 32

[5]See Figure 12, Page 33

DISCUSSION

At the outset of this discussion a brief statement as to the cause of knocking is quoted from Jost.[6] "The origin of knocking is as follows: The compressed mixture in the engine reaches a temperature that is quite high before ignition. This temperature further increases in the last part of the unburned charge as a consequence of compression by the progressing flame. These temperatures are so high that almost all fuels that are actually in use are subject to a rapid oxidation. It depends on the length of time that elapses between the development of an explosion from this rapid reaction whether the remnant of the charge reacts more or less instantaneously before the flame has progressed through the entire combustion chamber and whether knocking will occur or not."

According to Taylor and Taylor[7], any change in the operating conditions of an Otto engine which tends to lower the temperature of the last part of the fuel-air mixture to burn will reduce the tendency of the engine to knock. Also any factor which will cause an increase in the velocity of the flame front in the cylinder will lessen the tendency

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[6]Jost, Wilhelm, Explosion and Combustion Processes in Gases, (New York, McGraw-Hill Book Co. 1946) pp. 501-502

[7]Taylor, C. F., and Taylor, E. S., The Internal Combustion Engine, (Scranton, Penna., International Textbook Co., 1938) pp. 87-101

toward knocking. Obert[8] in addition mentions the fact that an increased ignition delay in the unburned portion is a fundamental factor in preventing knock. The engine variables which might possibly affect the three aforementioned items may be listed as follows[9]:

1. compression ratio
2. engine speed
3. air humidity
4. fuel-air ratio
5. jacket water temperature
6. intake manifold pressure
7. intake manifold temperature
8. spark advance.

Since the first six of the above variables were held practically constant during the test runs their effect on the detonation will not be relevent to this discussion. An increase in either the intake manifold temperature or the spark advance will cause an increase in the intensity of the knock[10] unless some type of knock supressor is introduced.

The injection of water into the fuel-air mixture entering the engine could possibly produce the following effects:

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[8]Obert, E. F., Internal Combustion Engines, (Scranton, Penna., International Textbook Co., 1950) pp.265-271

[9]Fraas, A. P., Combustion Engines, (New York, McGraw-Hill Book Co., 1948) pp.103-107

[10]Ibid., pp.104-105

(a) a lowering of the temperature of the charge entering the cylinder through evaporation of some of the water; (b) a lowering of the temperature of the charge after compression through evaporation of the water during compression (c) a lowering of the temperature of the charge after compression by a decrease in the polytropic exponent due to the increased number of triatomic molecules present during compression; (d) a lowering of the temperature of combustion by increasing the average specific heat of the mixture; and (e) an increase in the velocity of the flame front during the combustion. This last item may be explained in this manner. The speed with which the combustion reaction proceeds is proportional to the concentration of chain carriers (those radicals which will propagate the chain reaction) in the mixture[11]. The hydroxyl radical (OH) is one of the more important of these chain carriers and it is formed from the H_2O molecule at the temperatures at which the combustion reaction takes place[12]. Thus the concentration of chain carriers is increased by the addition of water to the mixture and therefore increases the velocity of the flame front. It can be seen that the injection of water into the fuel-air mixture entering the engine may act in

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[11]Obert, E. F., op. cit., p. 112

[12]Sidgwick, N. V., The Chemical Elements and their Compounds, (Oxford, At the Clarendon Press, 1950) p. 865

several different ways to suppress knock. As mentioned in the results of the test[13], the further the spark was advanced the more water was required to keep the knock intensity at the "borderline knock" level.

The injection of steam into the fuel-air mixture entering the engine could possibly cause: (a) a lowering of the temperature of the charge after compression by decreasing the value of the polytropic exponent; (b) a lowering of the temperature of combustion by increasing the average specific heat of the mixture; (c) an increase in the velocity of the flame front during the combustion; and (d) a decreased volumetric efficiency due to the volume occupied by the steam in the mixture. Again as mentioned in the results of the test[13], the further the spark was advanced the more steam was required to keep the knock intensity at the "borderline knock" level. A comparison of the quantity of steam injected with the quantity of water injected showed that for each case a greater quantity of steam was required to give the same degree of knock suppression that the water gave. It should be pointed out however, that the manifold temperature increased[14] with the injection of the steam thus causing the steam to have an additional knock intensifying factor to counteract. The increase in knock intensity due to the increased manifold temp-

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[13]See Figure 7, Page 28.

[14]See Figure 12, Page 33.

erature is relatively small, though, compared to the knock intensity increase caused by spark advance[15]. Lastly the steam injection caused a decrease in volumetric efficiency[16] which, because it reduces the weight of the charge inducted into the cylinder, tends to decrease the knock intensity slightly.

Other results of the injection of water and steam have been enumerated in the section on results of the test. The fact that the brake horsepower decreased[17] can be attributed to the fact that as the spark was advanced the peak pressure came sooner in the power stoke and thus reduced the effective pressure during expansion. Also for the case of steam injection the decrease in volumetric efficiency will lower even more the brake horsepower. The increase fuel consumption[18] is characteristic of increased spark advance.

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[15] Taylor, C. F., and Taylor, E. S., op. cit., pp. 96-98

[16] See Figure 11, Page 32.

[17] See Figure 8, Page 29.

[18] See Figure 9, Page 30.

CONCLUSIONS

The following conclusions can be drawn from this study of internal combustion engine performance as affected by the evaporation of water into the entering fuel and air mixture.

(a) Both the water and the steam were able to suppress detonation, but more steam was required than water to give the same degree of suppression. This can be attributed to the fact that the water is able to produce the same effects as the steam after it has evaporated and in addition it produces a good cooling effect as it is evaporated.

(b) There is no particular merit in simply advancing the spark and suppressing the detonation with water injections. However reference to the discussion[19] indicates that increasing the compression ratio will increase knocking. It will also increase the thermal efficiency of the Otto cycle, thus this test shows that we may increase the compression ratio to increase the thermal efficiency and suppress the accompanying knock increase by water injection.

(c) While steam is able to suppress detonation, it causes such decreases in power output, thermal efficiency and volumetric efficiency as to make its use as a detonation suppressant undesirable. However, water injection will allow an increase in horsepower due to suppressing detonation.

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[19] See Page 11.

Further studies could be made on this problem to determine the relative importance of decreasing the initial combustion temperature and increasing the velocity of the flame front.

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APPENDIX I

Diagrams and Photographs

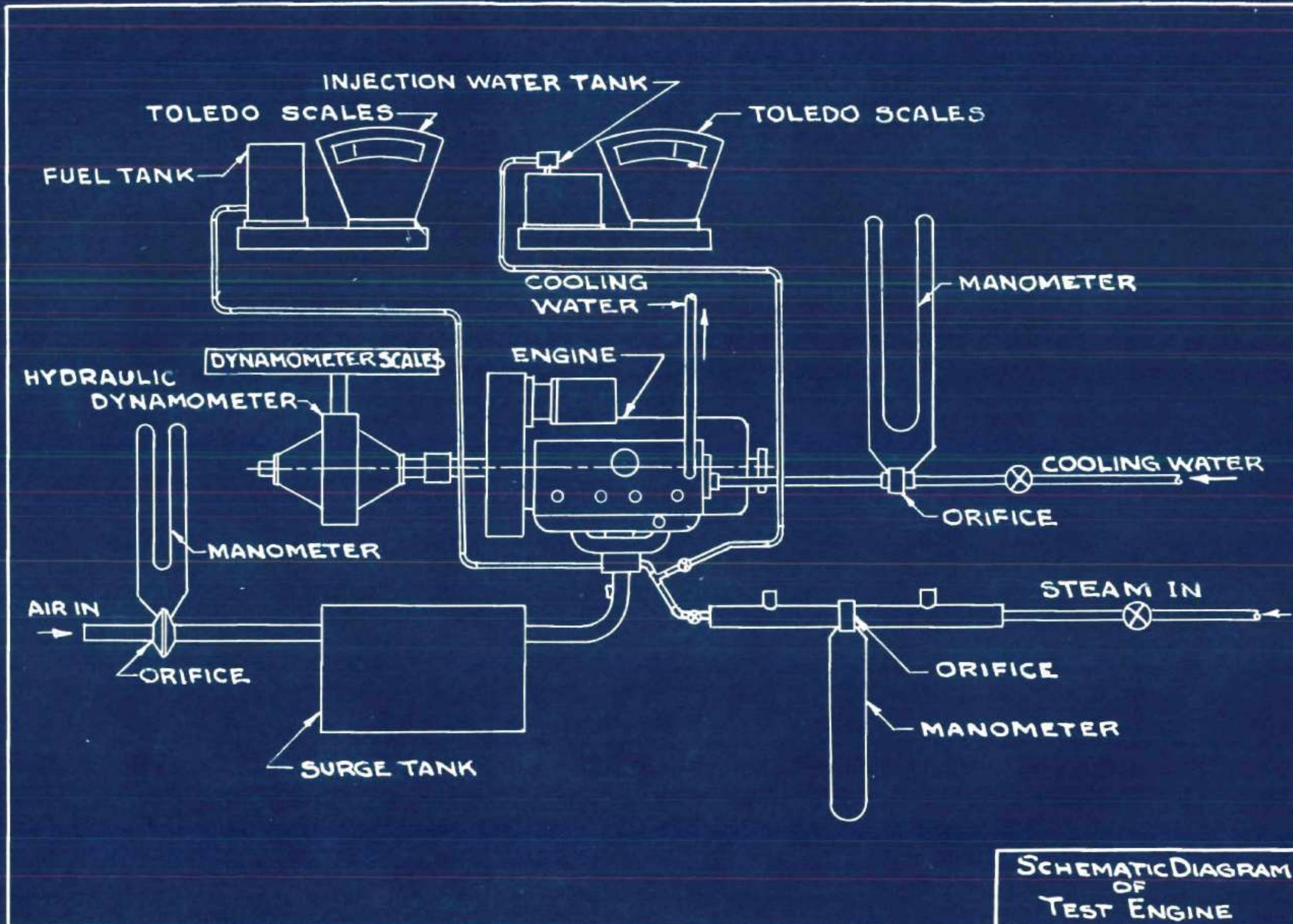

INJECTION WATER TANK
TOLEDO SCALES
TOLEDO SCALES
FUEL TANK
MANOMETER
COOLING WATER
DYNAMOMETER SCALES
ENGINE
HYDRAULIC DYNAMOMETER
COOLING WATER
ORIFICE
MANOMETER
STEAM IN
AIR IN
ORIFICE
ORIFICE
MANOMETER
SURGE TANK
SCHEMATIC DIAGRAM OF TEST ENGINE

FIGURE 1

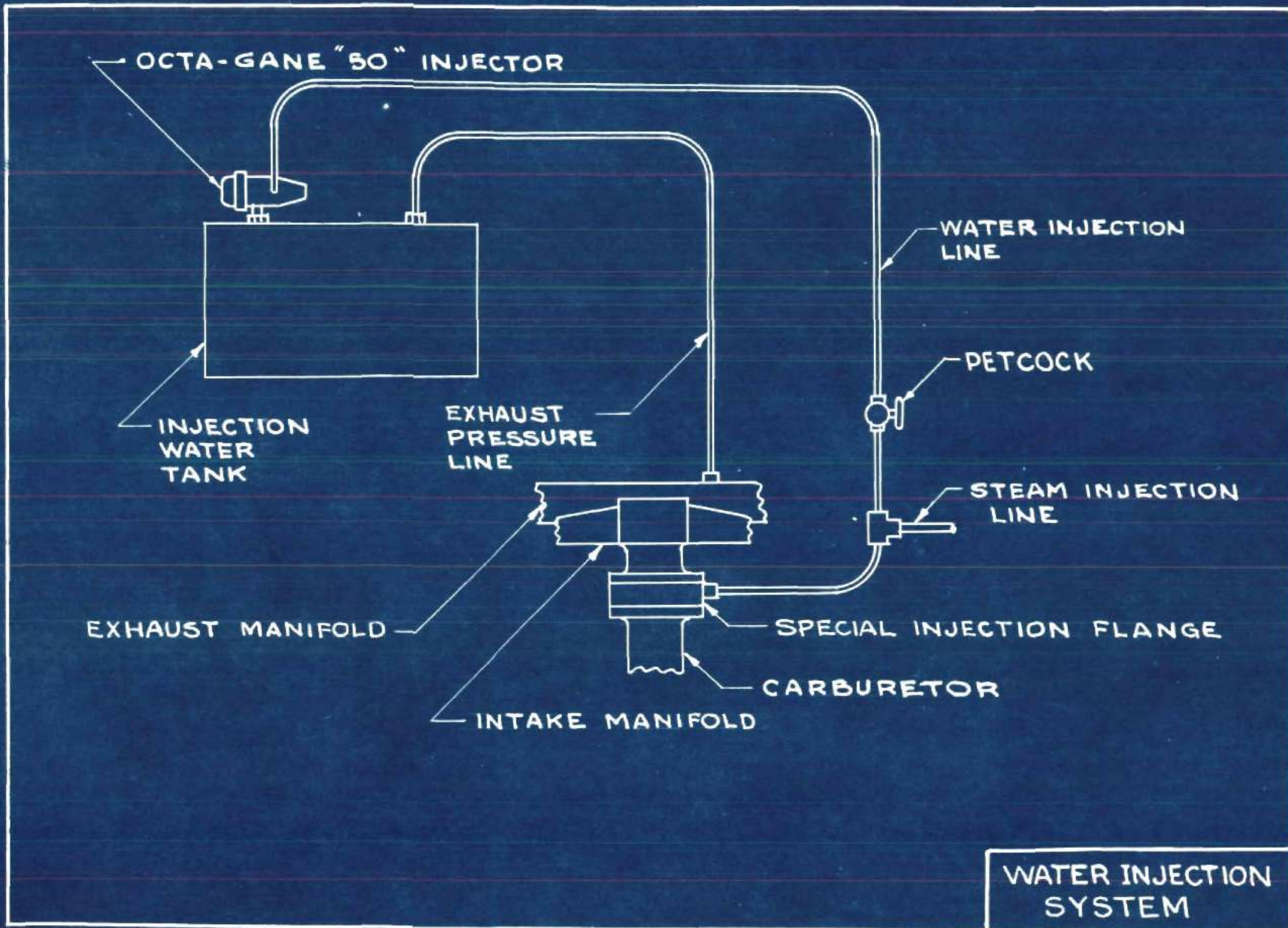

OCTA-GANE "50" INJECTOR
WATER INJECTION LINE
PETCOCK
INJECTION WATER TANK
EXHAUST PRESSURE LINE
STEAM INJECTION LINE
EXHAUST MANIFOLD
SPECIAL INJECTION FLANGE
CARBURETOR
INTAKE MANIFOLD
WATER INJECTION SYSTEM

FIGURE 2

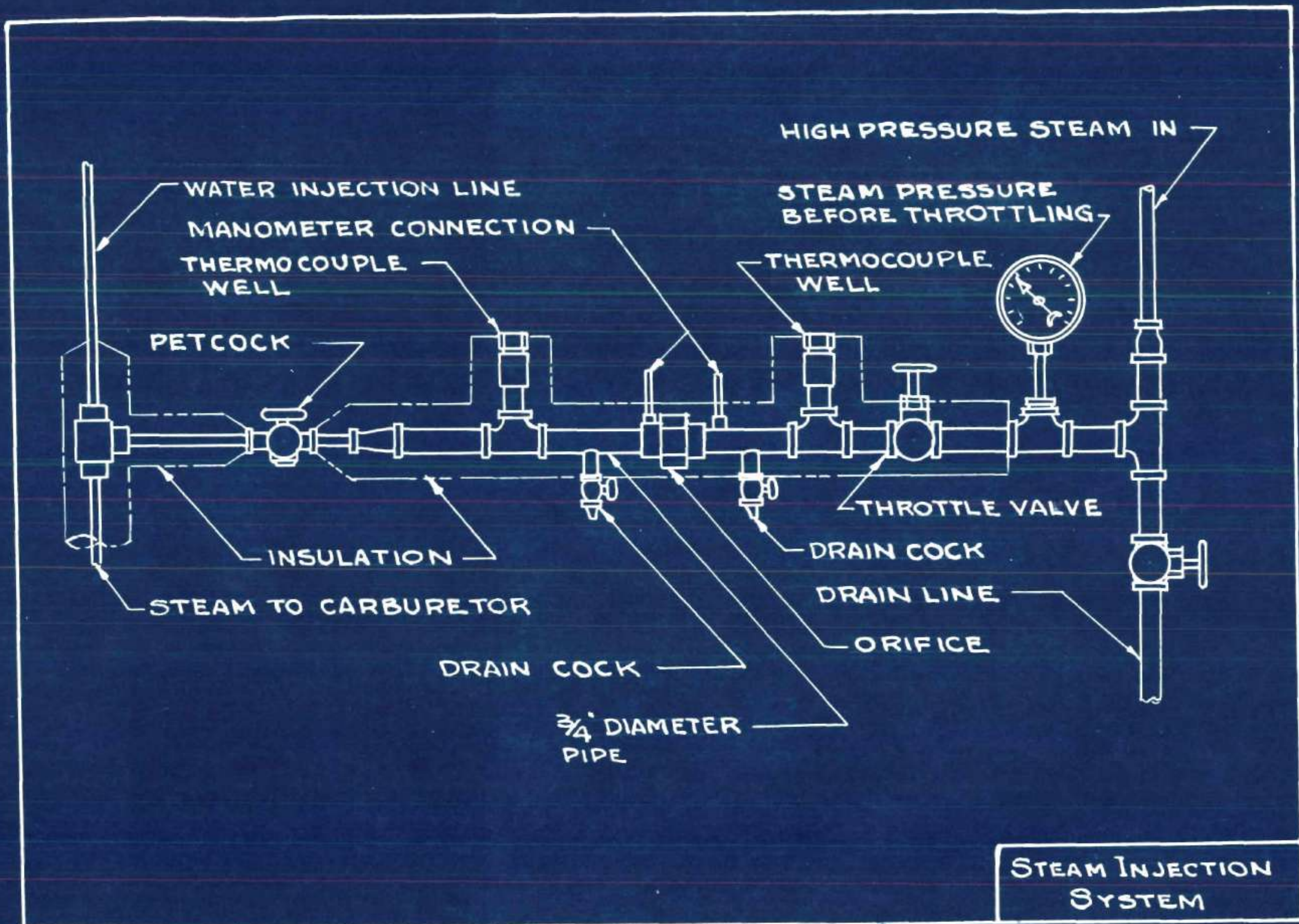

HIGH PRESSURE STEAM IN
WATER INJECTION LINE
STEAM PRESSURE BEFORE THROTTLING
MANOMETER CONNECTION
THERMOCOUPLE WELL
THERMOCOUPLE WELL
PETCOCK
THROTTLE VALVE
INSULATION
DRAIN COCK
DRAIN LINE
STEAM TO CARBURETOR
ORIFICE
DRAIN COCK
3/4" DIAMETER PIPE
STEAM INJECTION SYSTEM

FIGURE 3

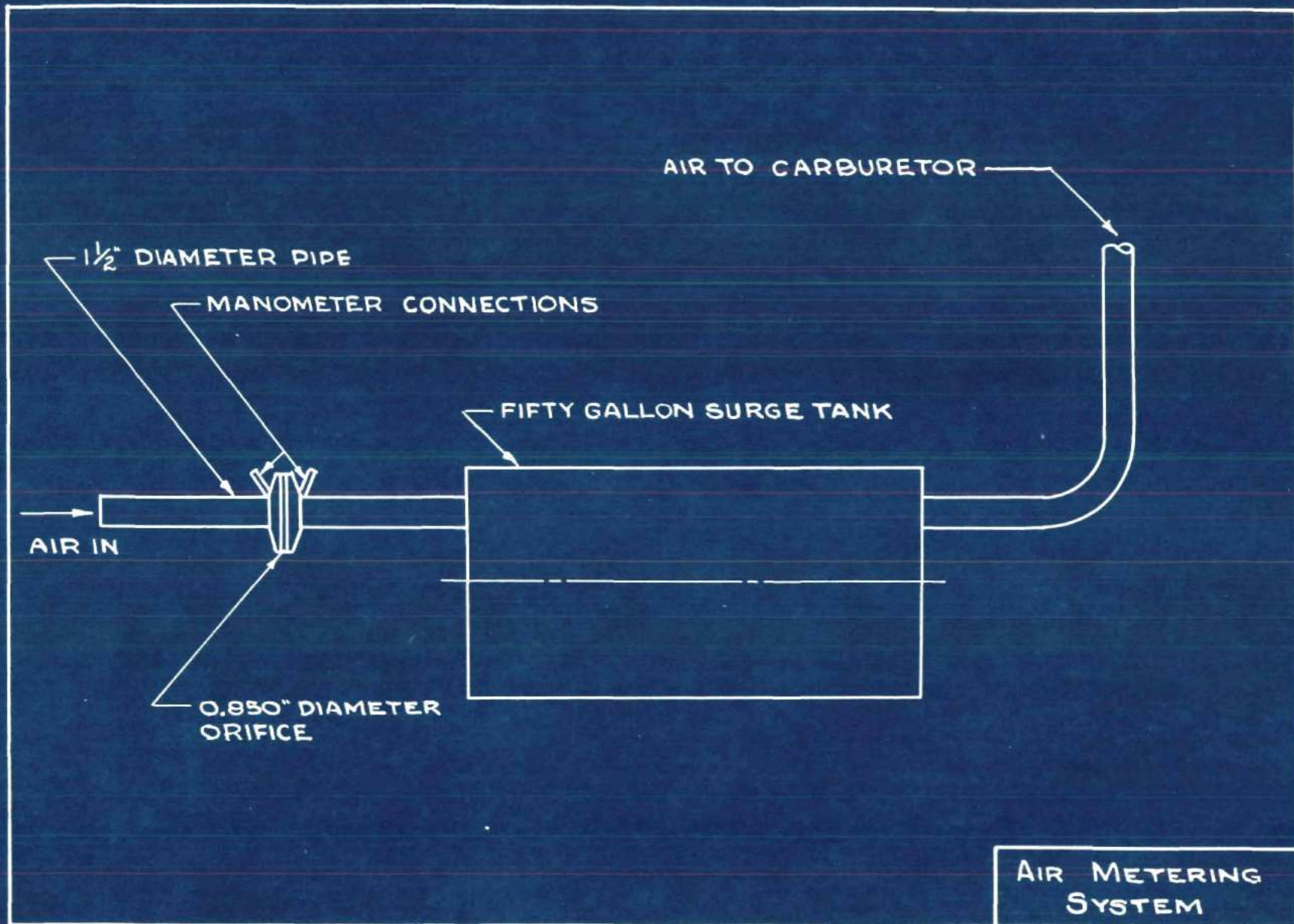

AIR TO CARBURETOR
1½" DIAMETER PIPE
MANOMETER CONNECTIONS
FIFTY GALLON SURGE TANK
AIR IN
0.850" DIAMETER
ORIFICE
AIR METERING
SYSTEM

FIGURE 4

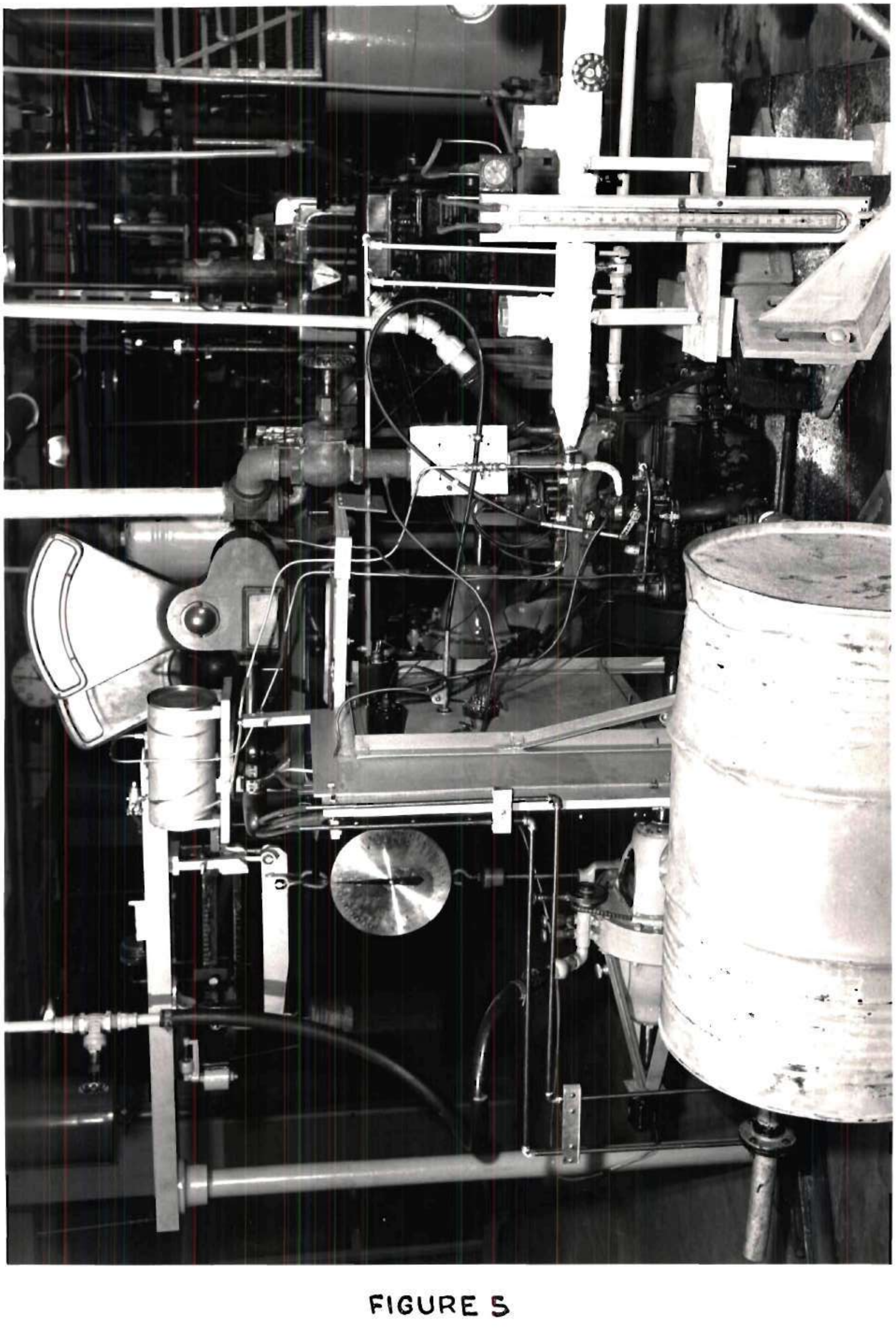


FIGURE 5

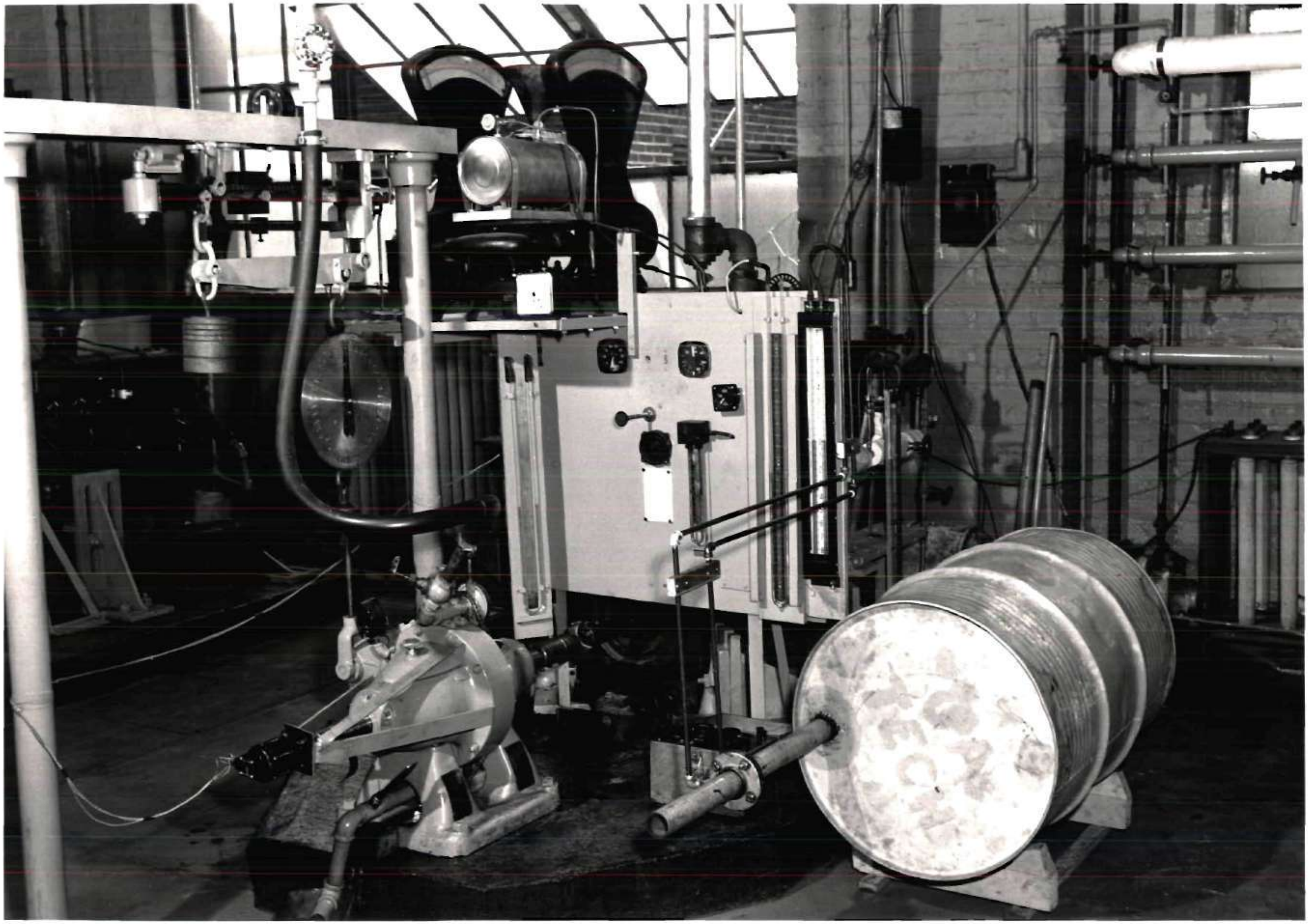


FIGURE 6

APPENDIX II

Tables and Curves

Table I - Performance Data of the Engine										
Run Number	Units	1	2	3	4	5	6	7	8	9
Spark Advance	°	40	45	50	55	60	45	50	55	60
Time of Test	Min.	15	20	15	15	15	15	15	15	15
Weight Fuel Used	Lbs.	2.23	2.96	2.23	2.20	2.18	2.11	2.11	2.10	1.99
Weight Water Used	Lbs.	-	0.28	0.66	1.33	1.76	-	-	-	-
Dynamometer Load	Lbs.	43.4	42.1	40.8	40.5	40.0	40.2	38.5	36.0	34.7
Engine Speed	R.P.M.	1800	1800	1800	1800	1800	1800	1800	1800	1800
Manifold Vacuum	In. Hg.	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Exhaust Pressure	In. Hg.	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Cooling Water Manometer	In. CCl_4	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Air Flow Manometer	In. H_2O	7.2	7.2	7.2	7.2	7.2	6.7	6.3	5.9	5.3
Room Dry Bulb Temperature	°F	81.0	81.0	82.0	84.0	84.0	85.0	85.0	84.0	86.0
Room Wet Bulb Temperature	°F	68.0	68.0	69.0	69.0	69.0	69.0	68.0	68.0	69.0
Manifold Temperature	°F	78.8	75.9	74.3	73.4	73.4	86.0	94.1	98.6	117.1
Exhaust Temperature	°F	995	977	973	975	957	1005	975	972	926
Cooling Water Temperature	°F	148	153	151	150	147	150	150	151	144
Steam Flow Manometer	In. Hg.	-	-	-	-	-	0.9	3.5	5.3	13.1
Steam Temperature	°F	-	-	-	-	-	208.0	211.6	213.8	225.1

Table II Results of the Performance of the Engine

Run Number	Units	1	2	3	4	5	6	7	8	9
Brake Horsepower	H.P.	13.01	12.63	12.23	12.15	12.00	12.06	11.45	10.80	10.41
Brake Specific Fuel Consumption	Lbs./H.P.-Min.	0.686	0.703	0.729	0.724	0.727	0.700	0.737	0.777	0.765
Thermal Efficiency	%	18.19	17.75	17.12	17.25	17.18	17.85	16.18	16.08	16.33
Pounds Air Per Minute	Lbs/Min.	2.14	2.14	2.13	2.13	2.13	2.06	1.995	1.931	1.825
Air-Fuel Ratio	–	14.39	14.47	14.35	14.53	14.66	14.65	14.18	13.70	13.79
Pounds Water Injected Per Minute	Lbs/Min.	–	0.0140	0.0440	0.0886	0.1173	–	–	–	–
Pounds Steam Injected Per Minute	Lbs/Min.	–	–	–	–	–	0.048	0.100	0.125	0.194
Volumetric Efficiency	%	82.5	82.5	82.9	83.1	83.1	80.5	78.8	75.3	71.5
Temperature Change - Room To Intake Manifold	°F	-2.2	-5.1	-7.7	-10.6	-10.6	+1.0	+9.1	+14.6	+31.1

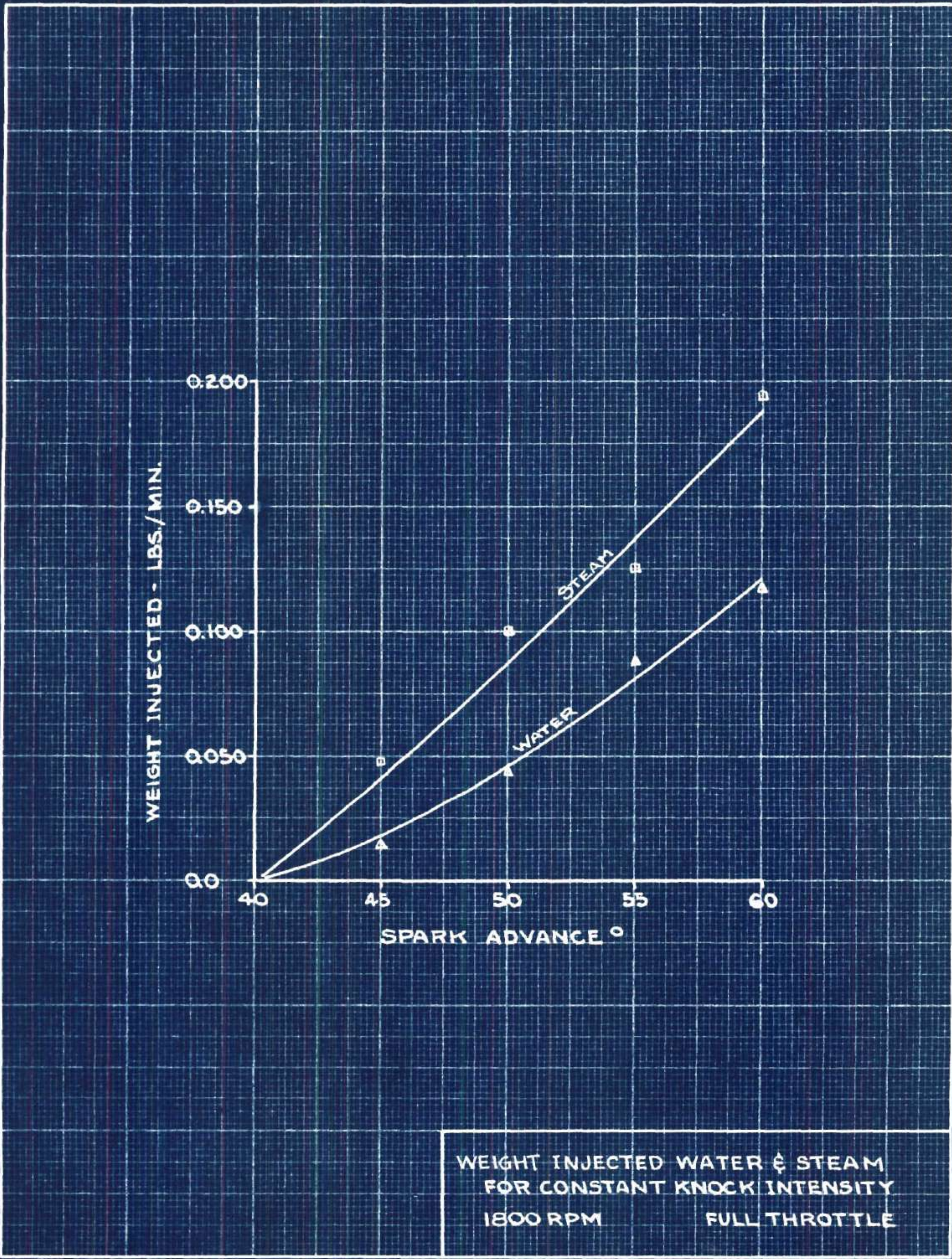
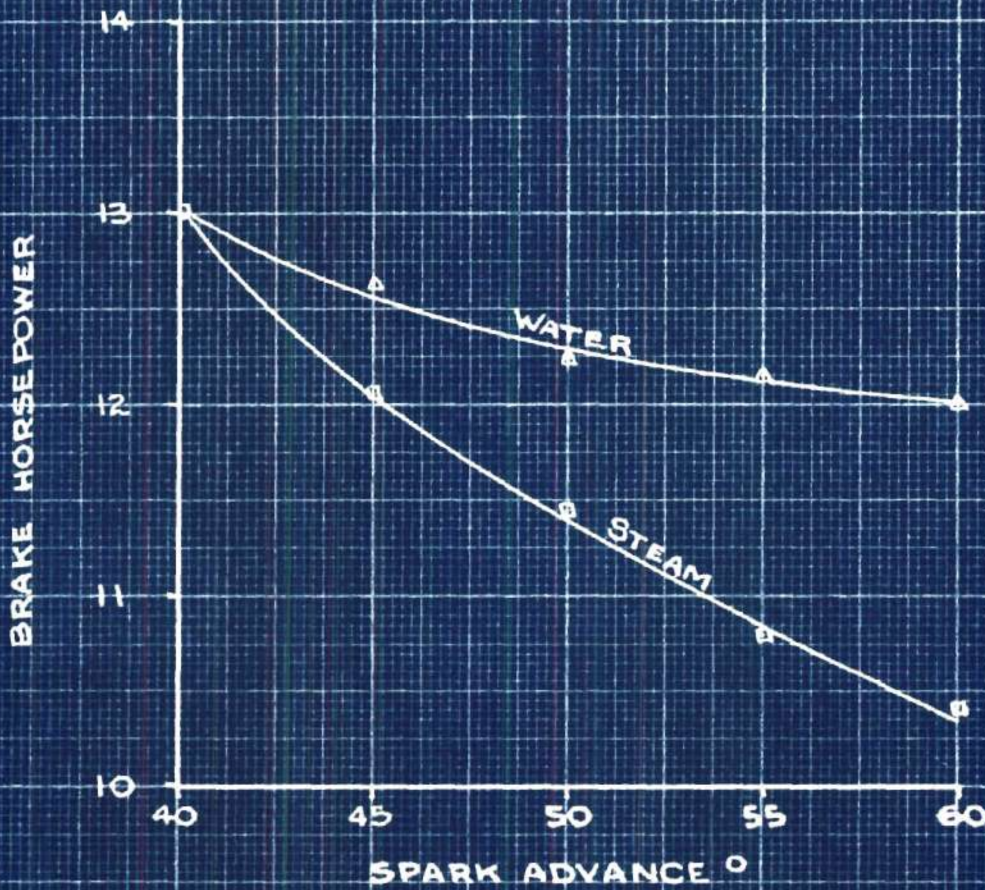
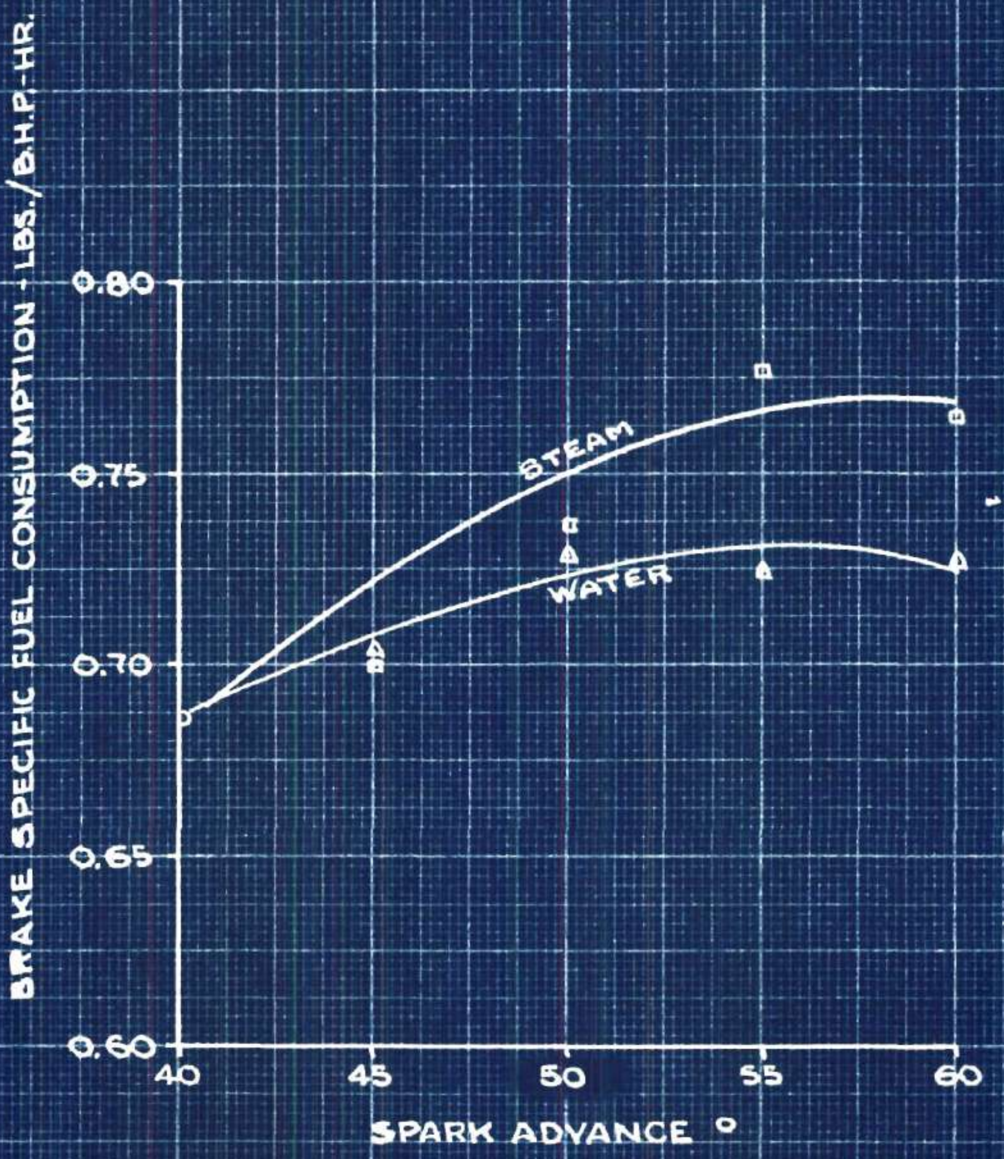

0.200
0.150
0.100
0.050
0.0
WEIGHT INJECTED - LBS./MIN.
STEAM
WATER
40
45
50
55
60
SPARK ADVANCE °
WEIGHT INJECTED WATER & STEAM
FOR CONSTANT KNOCK INTENSITY
1800 RPM
FULL THROTTLE

FIGURE 7



BRAKE HORSEPOWER
CONSTANT KNOCK INTENSITY
1800 RPM FULL THROTTLE

FIGURE 8



BRAKE SPECIFIC FUEL CONSUMPTION
CONSTANT KNOCK INTENSITY
1800 RPM FULL THROTTLE

FIGURE 9

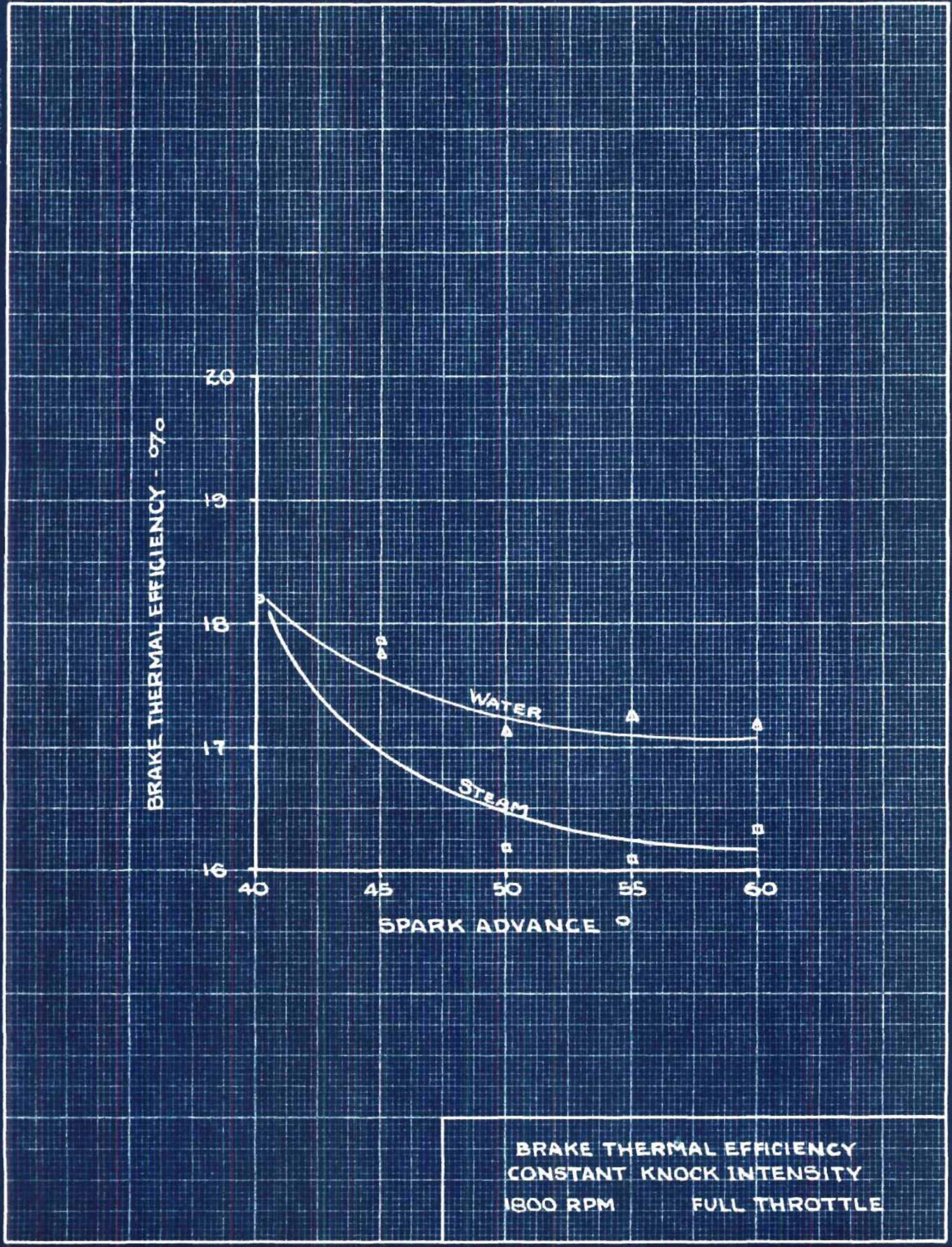
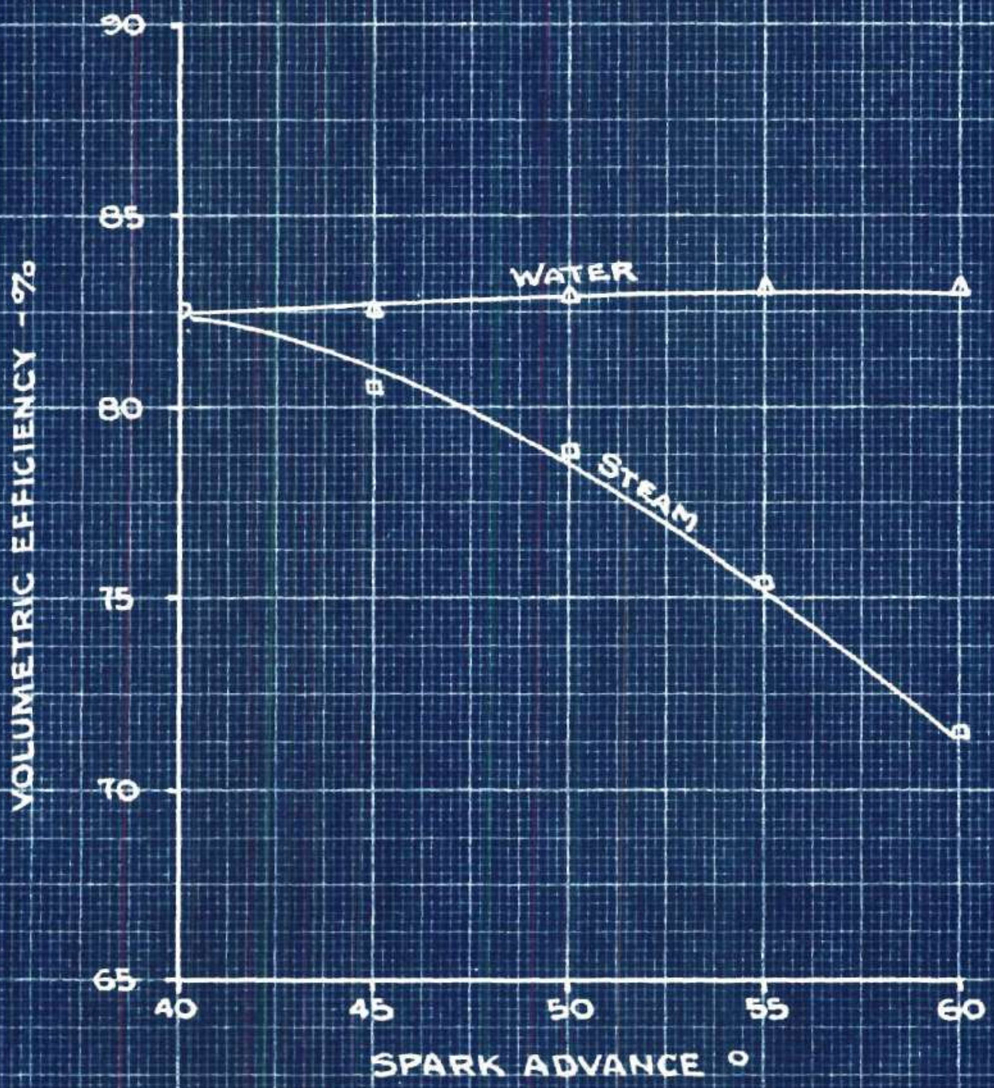
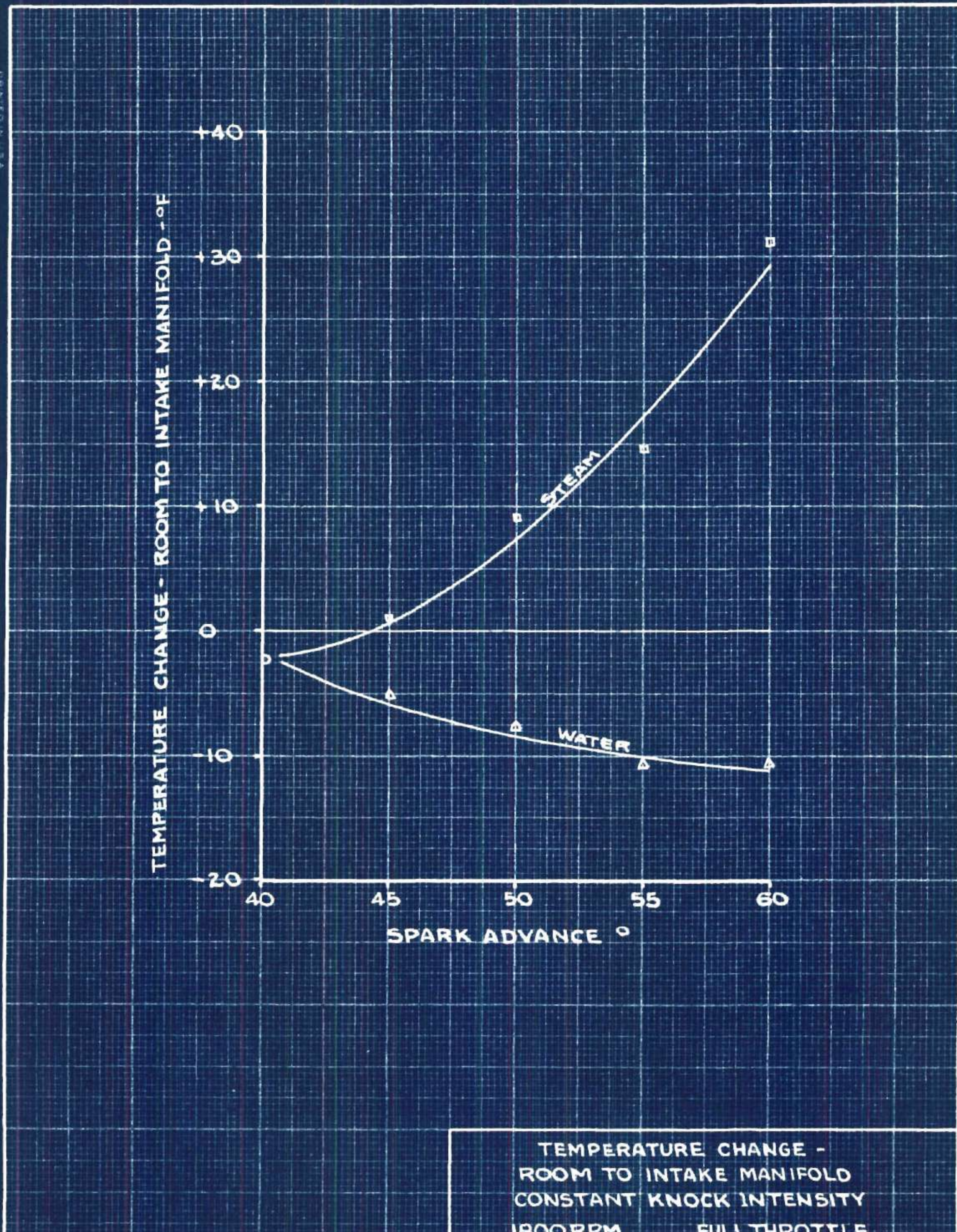

BRAKE THERMAL EFFICIENCY - %
20
19
18
17
16
40
45
50
55
60
SPARK ADVANCE °
WATER
STEAM
BRAKE THERMAL EFFICIENCY
CONSTANT KNOCK INTENSITY
1800 RPM
FULL THROTTLE

FIGURE 10



VOLUMETRIC EFFICIENCY
CONSTANT KNOCK INTENSITY
1800 RPM FULL THROTTLE

FIGURE 11



+40
+30
+20
+10
0
-10
-20
TEMPERATURE CHANGE - ROOM TO INTAKE MANIFOLD - °F
40
45
50
55
60
SPARK ADVANCE °
STEAM
WATER
TEMPERATURE CHANGE -
ROOM TO INTAKE MANIFOLD
CONSTANT KNOCK INTENSITY
1800 RPM FULL THROTTLE

FIGURE 12

APPENDIX III

Sample Calculations

SAMPLE CALCULATIONS

$$\text{B. H. P.} = \frac{\text{dynamometer load x R. P. M.}}{6000}$$

$$\text{B. H. P.} = \frac{43.4 \times 1800}{6000} = 13.01$$

$$\text{B. S. F. C.} = \frac{\text{pounds fuel / hour}}{\text{B. H. P.}}$$

$$\text{B. S. F. C.} = \frac{2.23 \times 4}{13.01} = 0.686 \text{ lbs. / B. H. P.-hr.}$$

$$\text{Thermal efficiency} = \frac{2545}{20{,}000 \times \text{B. S. F. C.}}$$

$$\text{Thermal efficiency} = \frac{2545}{20{,}000 \times 0.686} = 18.19\%$$

$$\text{Pounds air / min.} = 2.97 \sqrt{\frac{h_1 - h_2}{v_1}}$$

$$\text{Pounds air / min.} = 2.97 \sqrt{\frac{7.2}{13.88}} = 2.14$$

$$\text{Air-fuel ratio} = \frac{2.14}{2.23/15} = 14.39$$

$$\text{Volumetric efficiency} = \frac{\text{lbs. air/min. x specific volume}}{\text{Piston displacement}}$$

$$\text{Volumetric efficiency} = \frac{2.14 \times 13.88}{38.5} = 82.5\%$$

APPENDIX IV

Equipment

AIR METERING SYSTEM

To measure the quantity of air used by the engine a thin plate orifice was used in conjunction with a surge tank to damp out the pulsations of the incoming air.

The orifice, 0.850 inches in diameter and 0.054 inches thick, was installed between standard flanges in a 1 1/2 inch nominal diameter pipe. The manometer was connected to 0.054 diameter corner taps. (See Figure 4, Page 22)

The following equation given by Ower[20]:

$$G = a\, a_2\, g \sqrt{\frac{2 \rho_1 (p_1' - p_2')}{1 - m^2}} \qquad (1)$$

where G is the rate of flow in pounds/second^2.

a is the discharge coefficient.

a_2 is the orifice area in feet^2.

g is the acceleration of gravity in feet/second^2.

ρ_1 is the up-stream air density in slugs/foot^3.

p_1' is the pressure above the orifice in pounds/foot^2 absolute.

p_2' is the pressure below the orifice in pounds/foot^2 absolute.

m is the ratio of the orifice area to the pipe area.

may be used when $p_2' / p_1' \geqq 0.98$. Also according to Hodgson[20]

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[20] E. Ower, The Measurement of Air Flow, (London, Chapman and Hall Ltd., 1949) pp. 108-118.

when $m \leqq 0.49$ and the pressure taps are at the upstream and downstream planes of the orifice plate a discharge coefficient of 0.608 may be used with not more than one per cent error. Since the orifice used in this test meets the above requirements, equation (1) may be used to determine the rate of air flow.

From equation (1), by arranging terms and collecting constants and conversion factors, the following equation results:

$$G' = 2.97 \sqrt{\frac{h_1 - h_2}{v_1}} \qquad (2)$$

where G' is the rate of flow in pounds/minute.

$h_1 - h_2$ is the pressure drop across the orifice in inches of water.

v_1 is the specific volume of the upstream air.

2.97 is the constant obtained by taking all conversion factors and other constants and combining them into one.

The only terms to be determined in equation (2) are the specific volume of the upstream air and the pressure drop across the orifice. The specific volume of the upstream air may be obtained from a psychrometric chart using the wet and dry bulb temperatures of the atmosphere. The pressure drop across the orifice is read from the manometer as indicated.

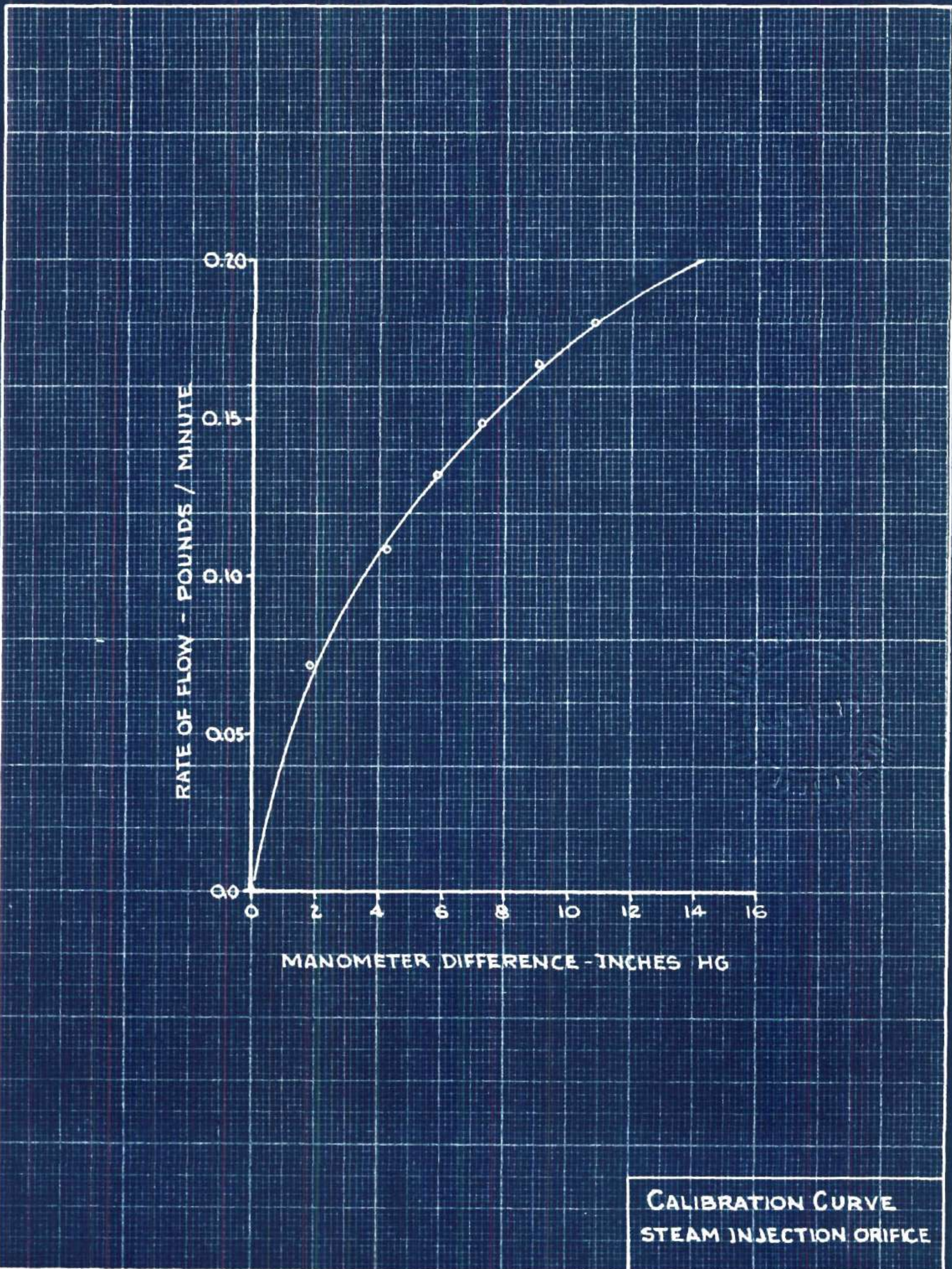
0.20
0.15
0.10
0.05
0.0
RATE OF FLOW - POUNDS / MINUTE
0
2
4
6
8
10
12
14
16
MANOMETER DIFFERENCE - INCHES HG
CALIBRATION CURVE
STEAM INJECTION ORIFICE

FIGURE 13

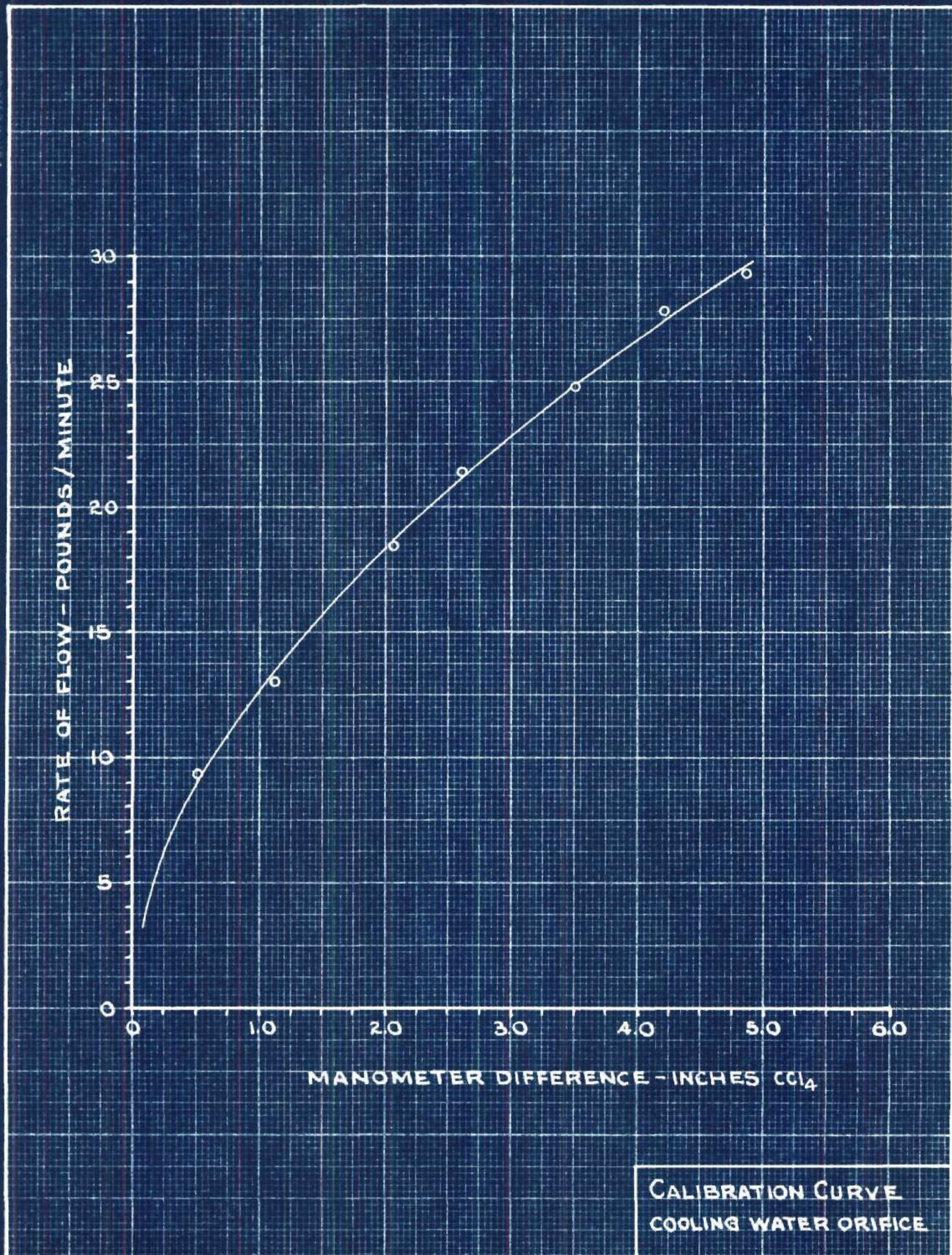
30
25
20
15
10
5
0
RATE OF FLOW - POUNDS / MINUTE
0
1.0
2.0
3.0
4.0
5.0
6.0
MANOMETER DIFFERENCE - INCHES CCl_4
CALIBRATION CURVE
COOLING WATER ORIFICE

FIGURE 14